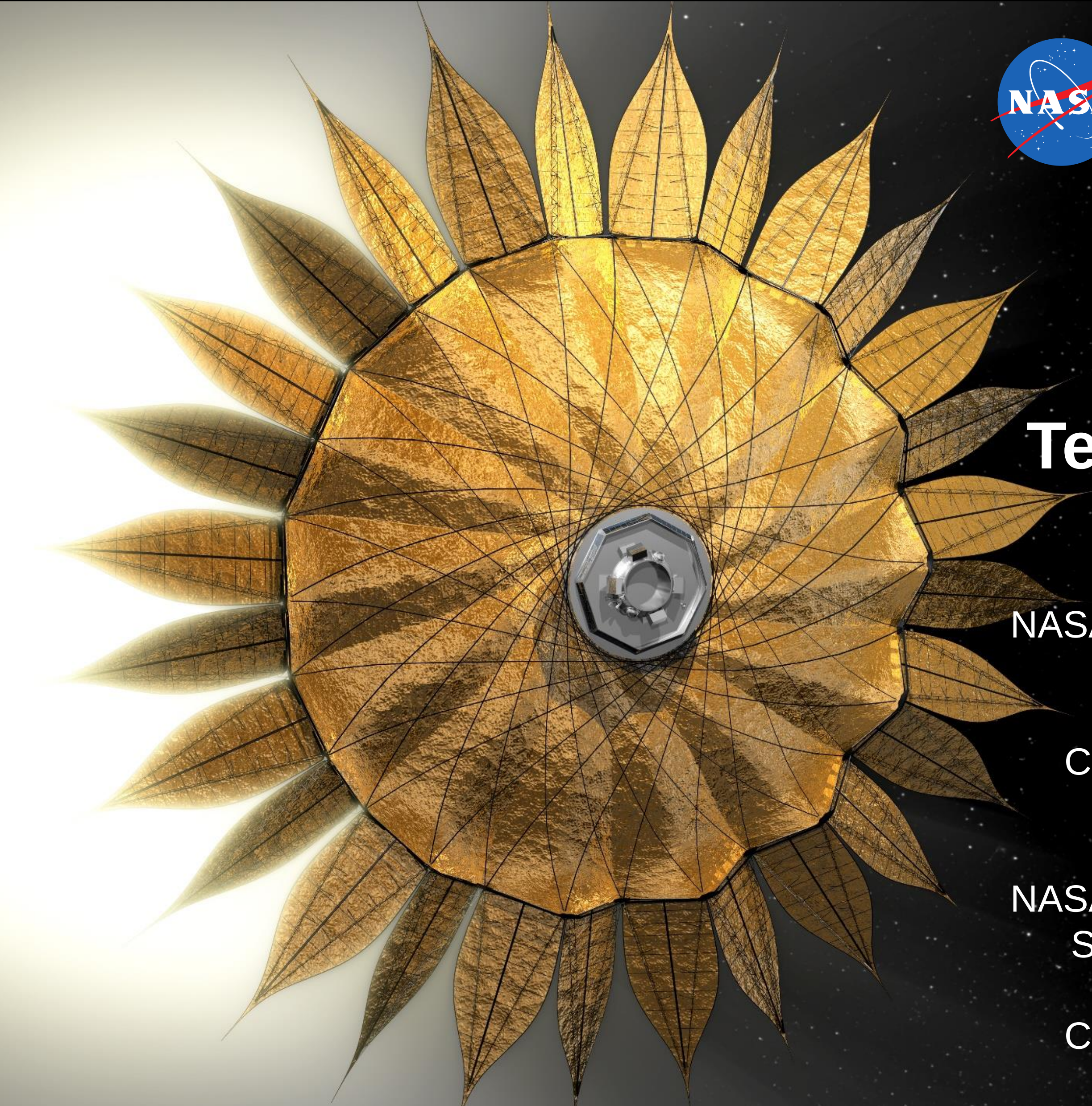

Jet Propulsion Laboratory
California Institute of Technology

Starshade Technology Activity

Dr. Nick Siegler
NASA Exoplanets Exploration Program
Chief Technologist
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Dr. John Ziemer
NASA Exoplanets Exploration Program
Starshade Technology Manager
Jet Propulsion Laboratory
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The decision to implement a starshade mission will not be finalized until after the 2020 Astrophysics Decadal Survey and NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

November 16, 2017 **SPIE Mirror Technology Workshop**

SMD Charters Starshade Tech Project (March 2016)

Objective to get to TRL 5

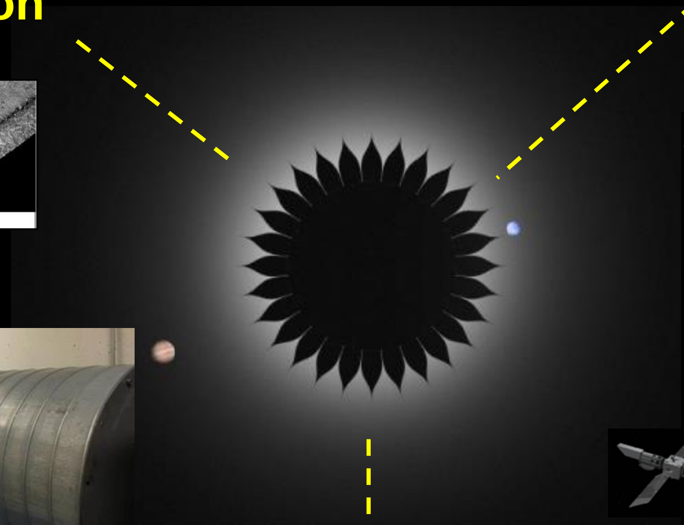
Project Goals:

- Develop starshade technology to discover Earth-like planets in habitable zones around Sun-like stars for future space telescope missions.

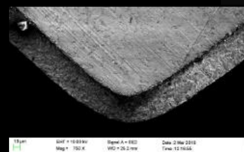
- *Advance the technologies that close the three key technology gaps to TRL 5*

- NASA will make no decision on conducting a starshade mission until after the 2020 Decadal Survey

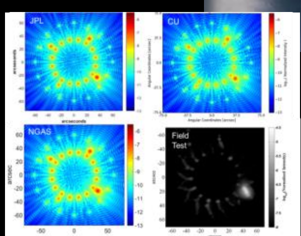
The Three Starshade Technology Gaps



(1) Starlight Suppression

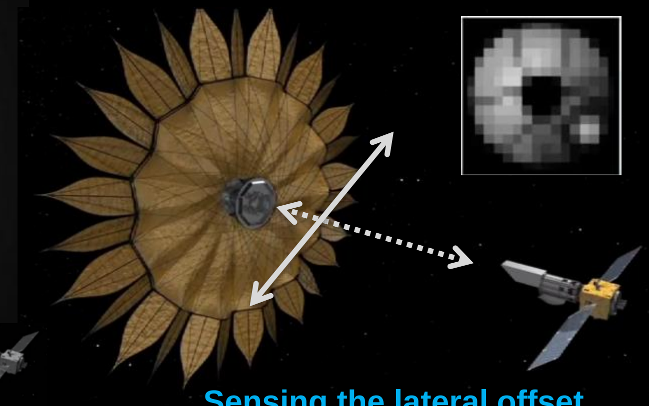


Suppressing scatted light off petal edges from off-axis Sunlight (S-1)



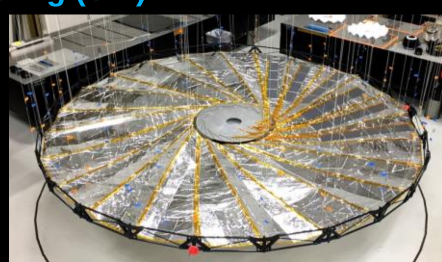
Suppressing diffracted light from on-axis starlight and optical modeling (S-2)

(2) Formation Sensing

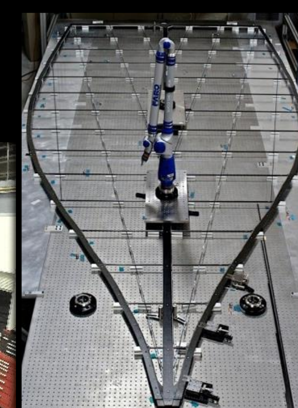


Sensing the lateral offset between the spacecraft (S-3)

(3) Deployment Accuracy and Shape Stability



Positioning the petals to high accuracy, blocking on-axis starlight, maintaining overall shape on a highly stable structure (S-5)



Fabricating the petals to high accuracy (S-4)

S-# corresponds to ExEP Starshade Technology Gap (http://exoplanets.nasa.gov/exep/technology/gap-lists)

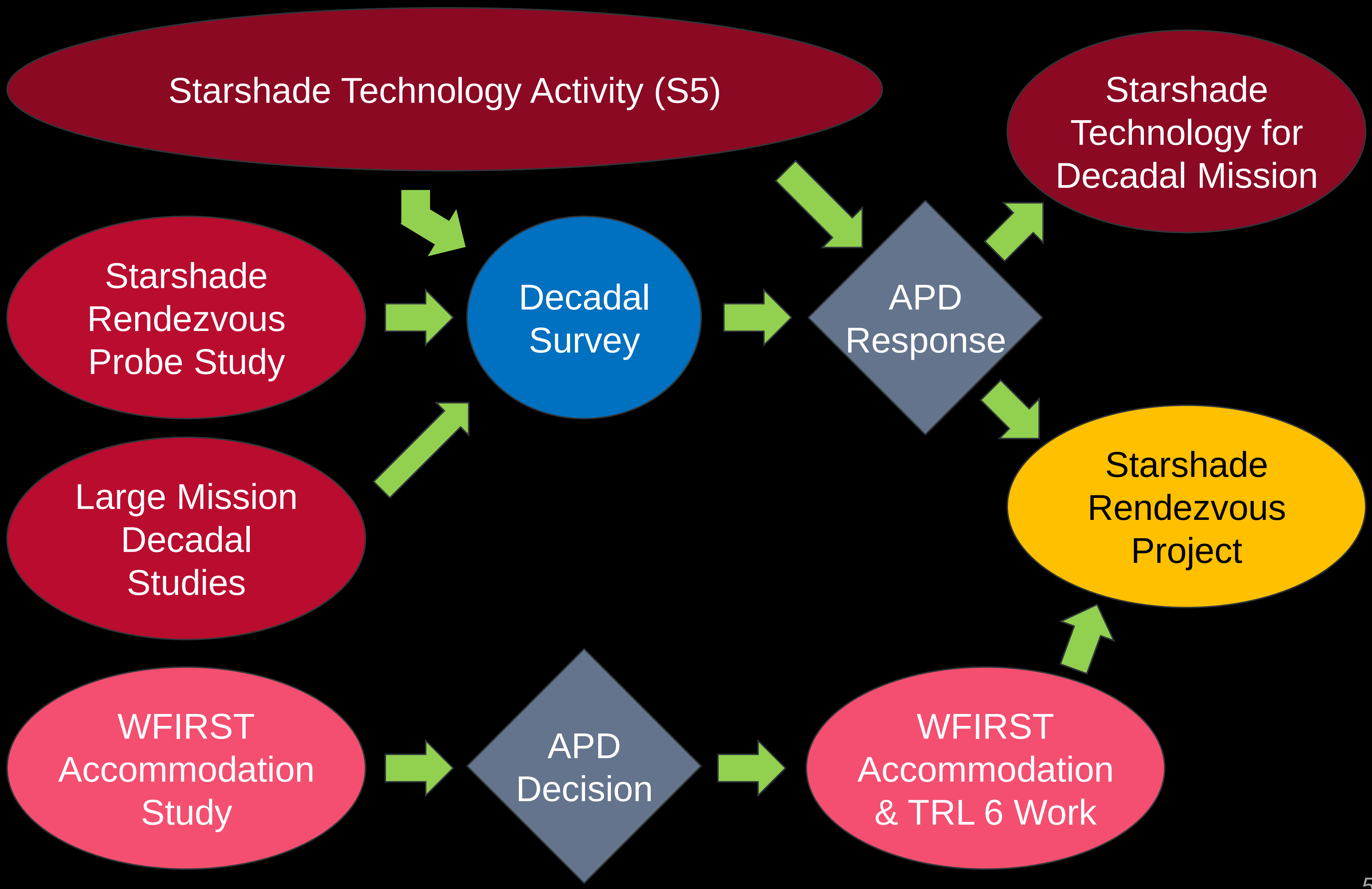
Keys to Success

- Must be ready for 2020 Astrophysics Decadal
  - Key technologies need to be mature enough to enable a starshade to be considered for possible WFIRST Rendezvous and future large telescope missions
  - Complete near-term milestones of an approved TRL 5 Plan
  - Reach TRL 5 on several key technologies before end of decade

- Starshade will live and flourish by its model validation
  - Performance models: optical diffraction, light scattering, mechanical, thermal and dynamic deformation, etc.
  - Ground based tests must focus on validating performance models and the error budget as well as demonstrations of meeting requirements that are derived from reasonable error budgets

- Independent reviews of the technology plan and technical progress

Ongoing Activities and Steps to Flight



Current Starshade Activities

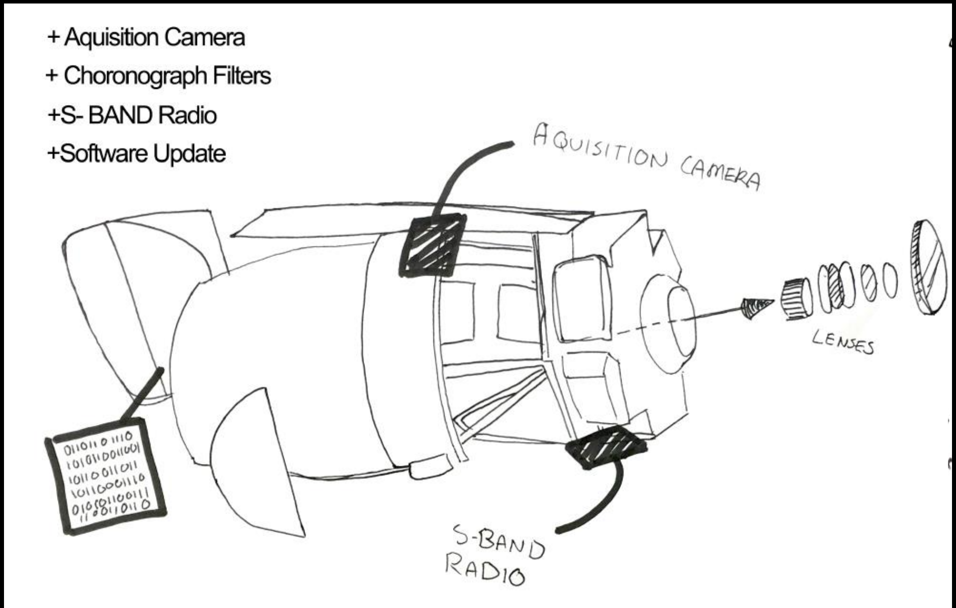
1. Starshade Technology Project (TRL 5)
   - Conducting mechanical architecture trade between folded and wrapped petal designs with Northrop Grumman and JPL teams
   - Preparing technology development plan for remaining work to reach TRL, which will be reviewed by NASA Astrophysics Division (APD) for approval
2. Decadal Survey mission concept (HabEx)
3. Decadal Survey probe study (WFIRST Rendezvous)
4. WFIRST Accommodation Study (with coronagraph)
5. In-space assembly study (100 m-class starshades)
6. Lots of new starshade SBIRs in all phases

All since 2016!!

Starshade Accommodation on WFIRST (Feb 2017)

Possibility of imaging an exo-Earth in the next decade

- SMD and APD continue to ask WFIRST Project to study starshade accommodation and its impact on the spacecraft and coronagraph
  - Descope options are available before and after the Project SRR
  - Possibility to demonstrate starshade technology in space (along with coronagraph technology) and observe habitability of near-by exoplanets
  - Final decision whether to fly a starshade mission awaits 2020 Decadal Survey recommendations



Recent Starshade Technology Activities and Future Plans

Optical Performance

Starlight Suppression

Need:

- Validate optical performance models through demonstrations achieving starlight suppression ≤ 10^{-9} in scaled flight-like geometry (flight-like Fresnel number) across a broadband optical bandpass
- Demonstrate that the validated models are traceable to ≤ 10^{-9} suppression system performance in space

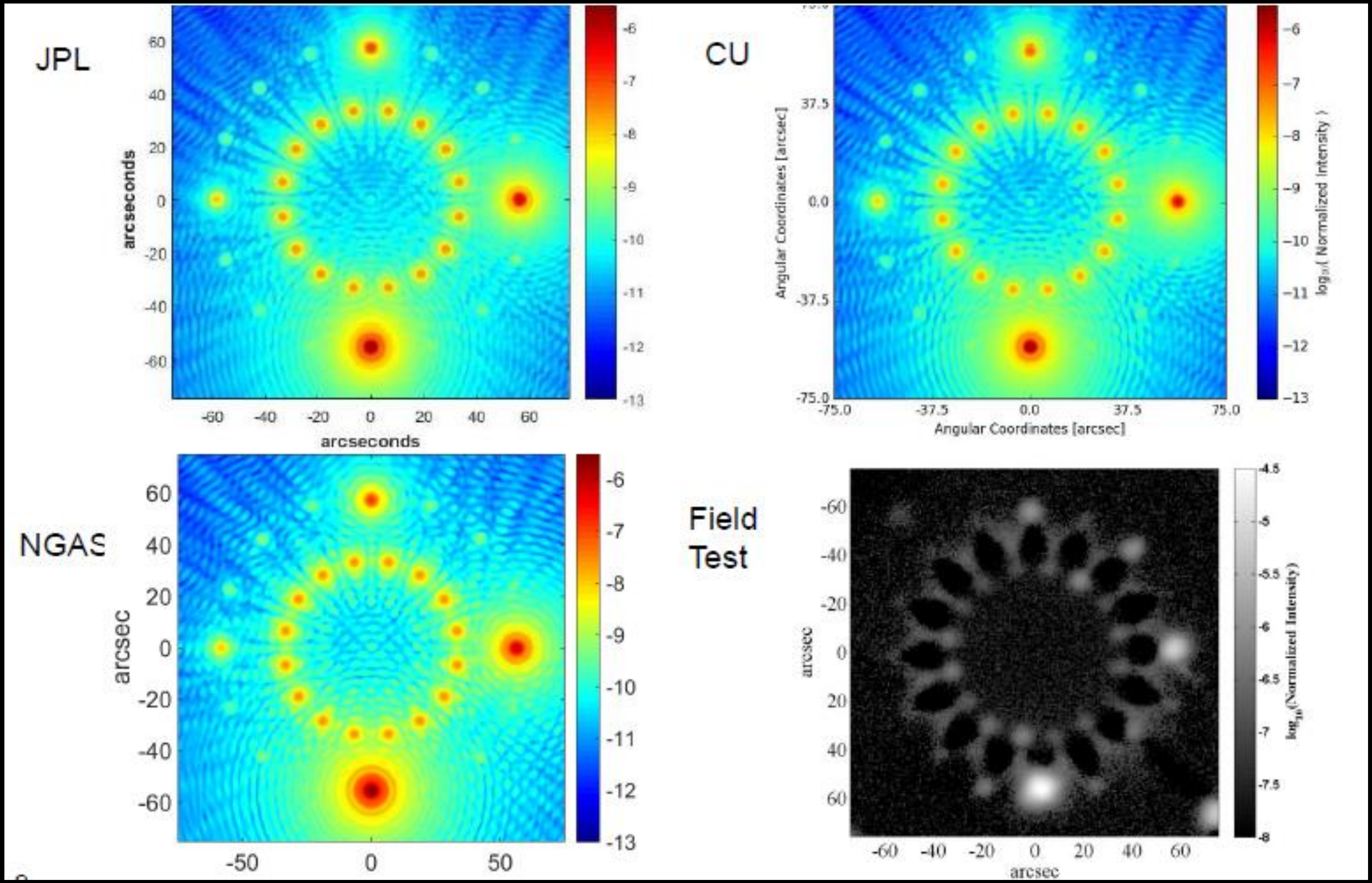
Current Capabilities:

- Flight sub-scaled demonstration being conducted on the Princeton Optical Testbed have achieved 3×10^{-8} suppression.
- Models and testbed results are converging

Optical Performance

Optical Modeling Convergence (Desert Test)

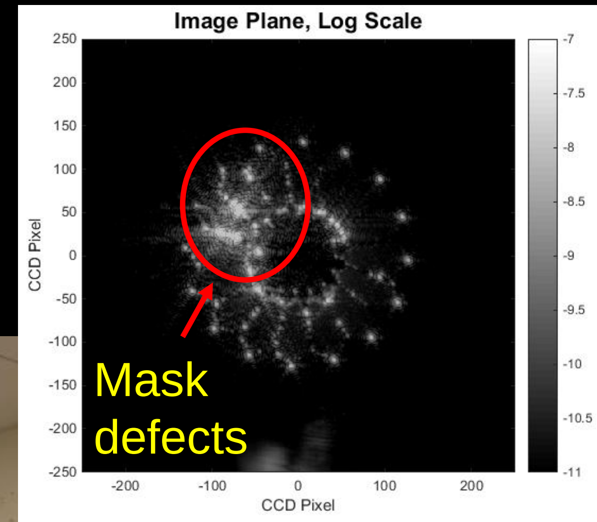
Intentionally flawed starshade

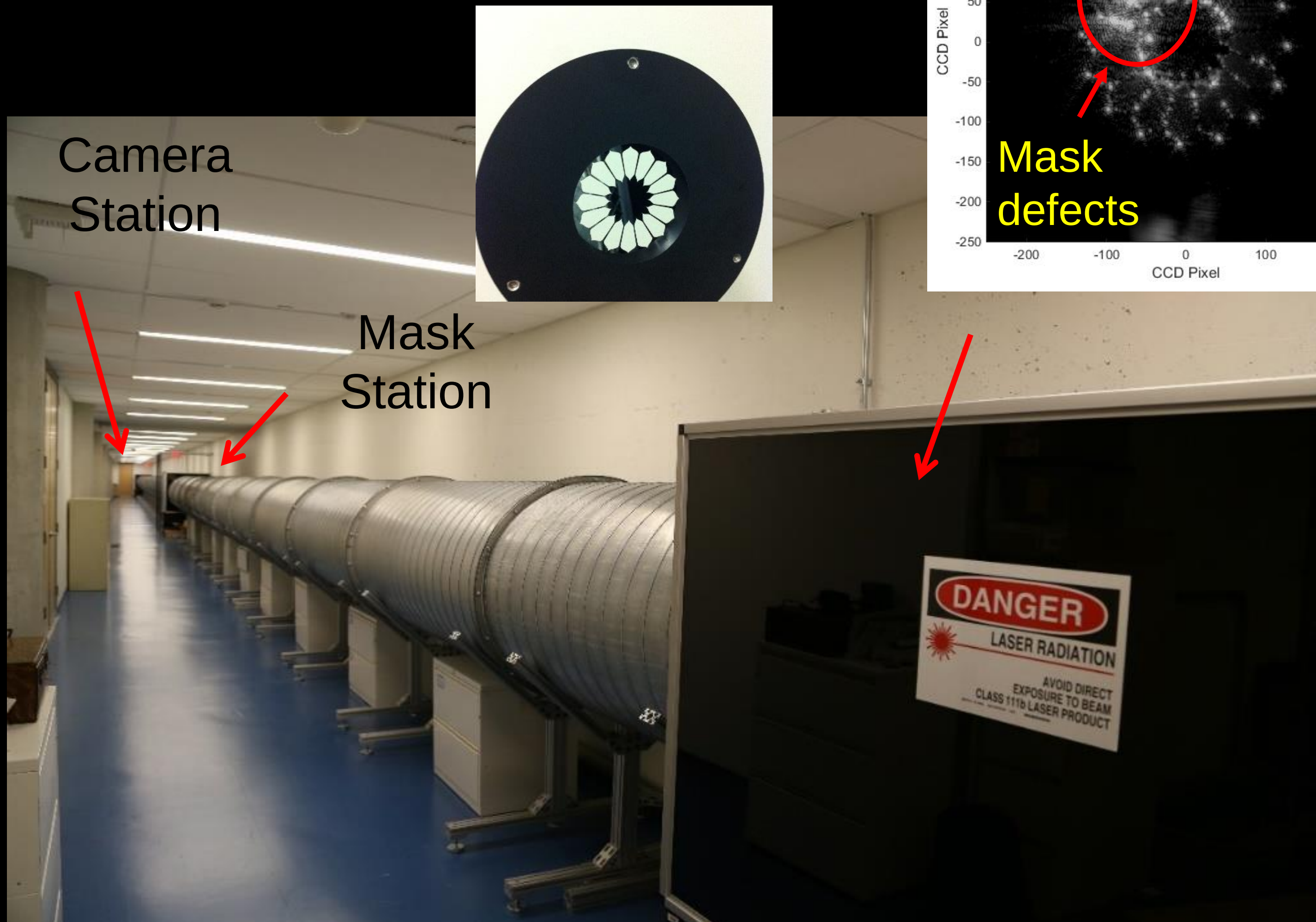


POC: Jeremy Kasdin (Princeton), Web Cash/Anthony Harness (UC-Boulder), Steve Warwick (NGAS), Stuart Shaklan (JPL)

Optical Performance

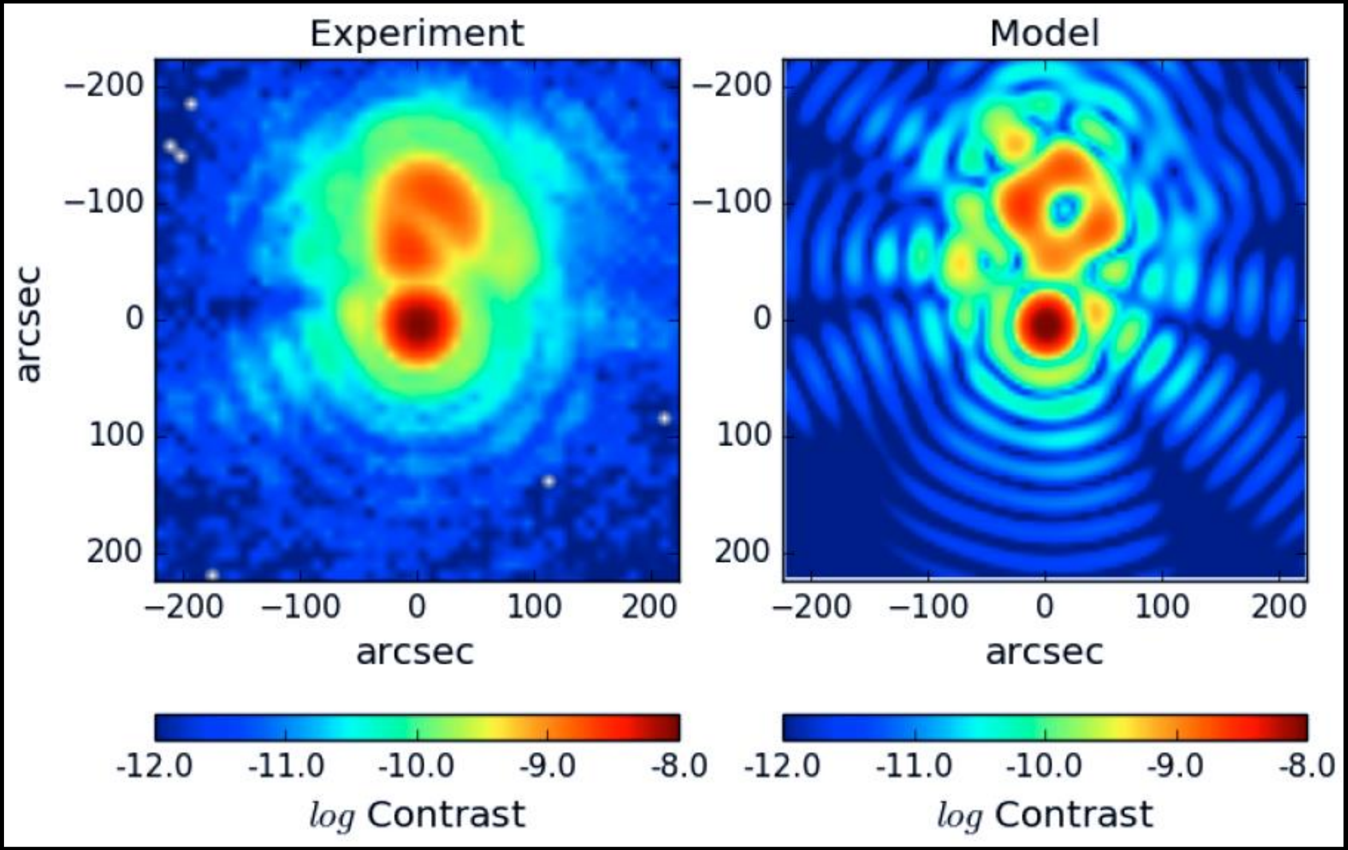
Starshade Testbed at Princeton University





Optical Performance

Testbed Data – Modeling Converging (Princeton Testbed)



Harness et al SPIE 2016

Optical Performance

Starlight Suppression (S-2)

Plan to Close Gap:

- Continually improving models for higher fidelity simulation (e.g. out of plane defects, in-air ground test modeling and validation) and error budget validation

- Plan to measure ultimate contrast with well fabricated starshade mask in Princeton testbed by December 2017

- Areas for future focus to reach TRL 5:
  - Optical performance model and error budget validation
  - Ground-based tests with intentionally defective starshades
  - Potential follow-on demonstrations (Workshop on October 10-11):
    - Additional wavelengths in Princeton Testbed
    - Larger scale testbed demonstration (XRCF, Hyperloop)
    - Additional in-air / starlight suppression demonstration for TRL 6

Petal Deployment Accuracy

Deployment Accuracy and Shape Stability (S-5)

Need:

- Deployment tolerances demonstrated to ≤ 1 mm (in-plane position) with flight-like, minimum half-scale structure, simulated petals, opaque structure, and interfaces to launch restraint after exposure to relevant environments
- Deploy petals with no edge damage

Current Capabilties:

- Petal deployment tolerance (≤ 1 mm) verified with low fidelity 12 m prototype and no optical shield; no environmental testing
- Optical shield prototypes fabricated and demonstrated
- Unfurling testbed being constructed

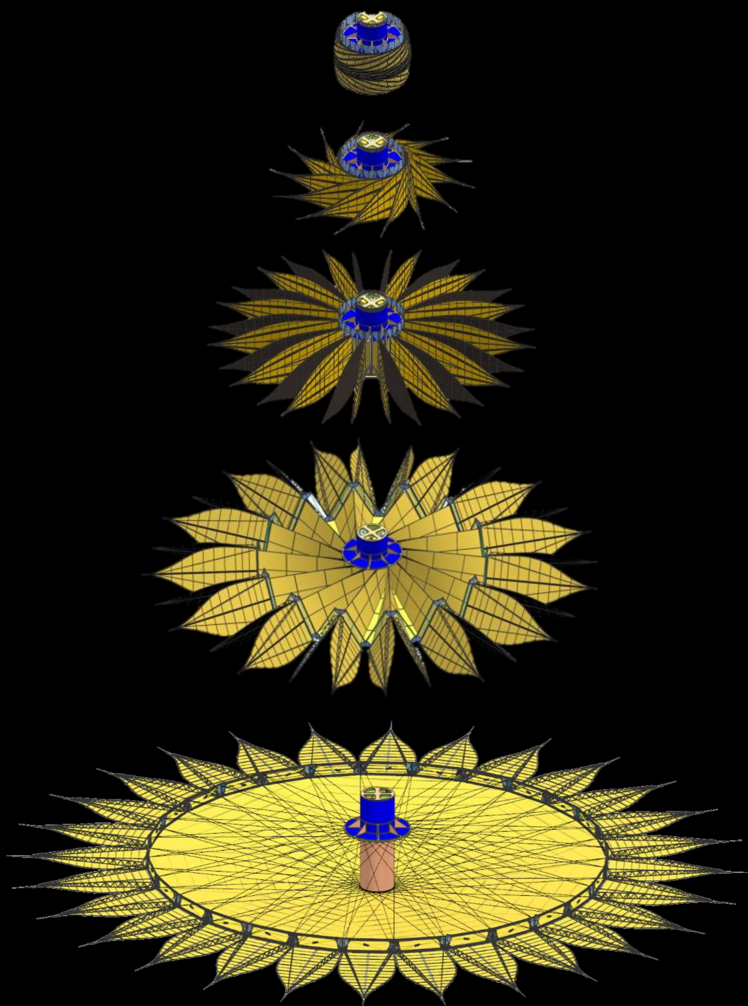
Mechanical Deployment Approaches

Trade Study Underway with Multi-Institutional Working Group

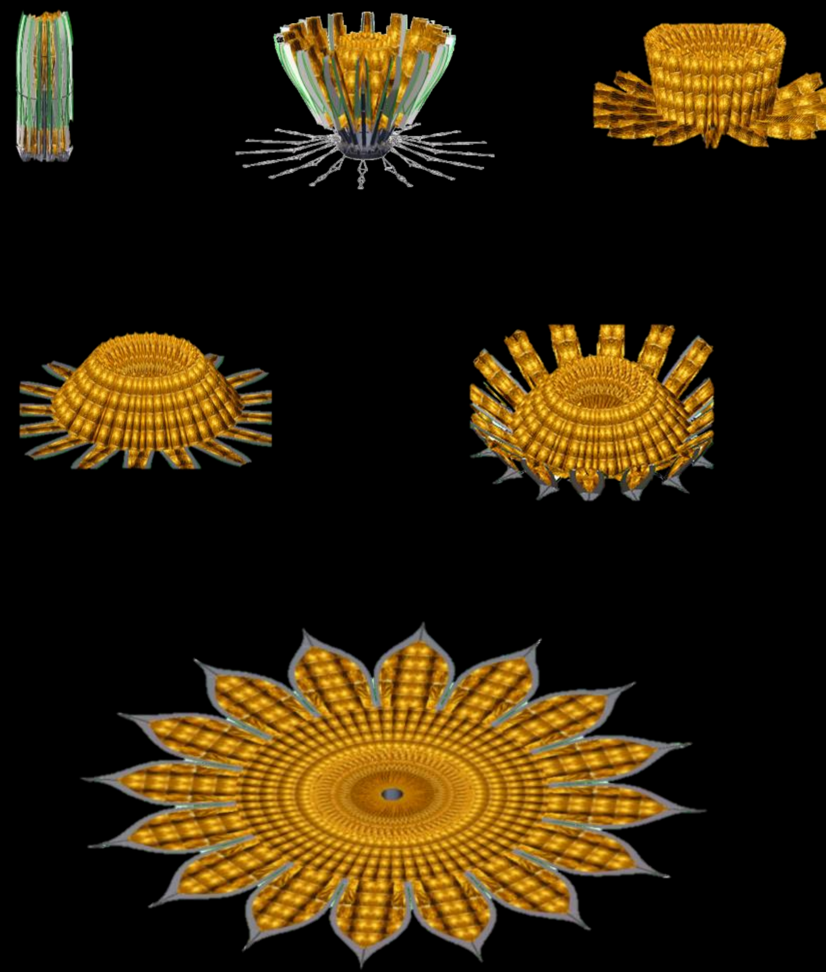
- Determine the best path forward on the starshade mechanical architecture for reaching TRL 5
  - Started in late September 2017, expected completion by end of March 2017
  - Examining two architectures with different stowage options: folded and wrapped petals that are deployed using actuators or mainly stored strain energy
- Independent Trade Evaluation Team (TET) will establish the trade criteria and evaluate trade options
  - Kendra Short (ExEP), Nick Siegler (ExEP), Joe Pitman (ExEP TAC), Keith Belvin (STMD), Sergio Pellegrino (Caltech), Keats Wilkie (LaRC), Kim Aaron (JPL), Dale Hoffman (retired NGAS)
- S5 manager will consolidate inputs & provide package to ExEP manager, who will recommend direction to Paul Hertz, who will decide the best way forward for starshade mechanical technology

Mechanical Deployment Approaches

Trade Study Underway with Multi-Institutional Working Group



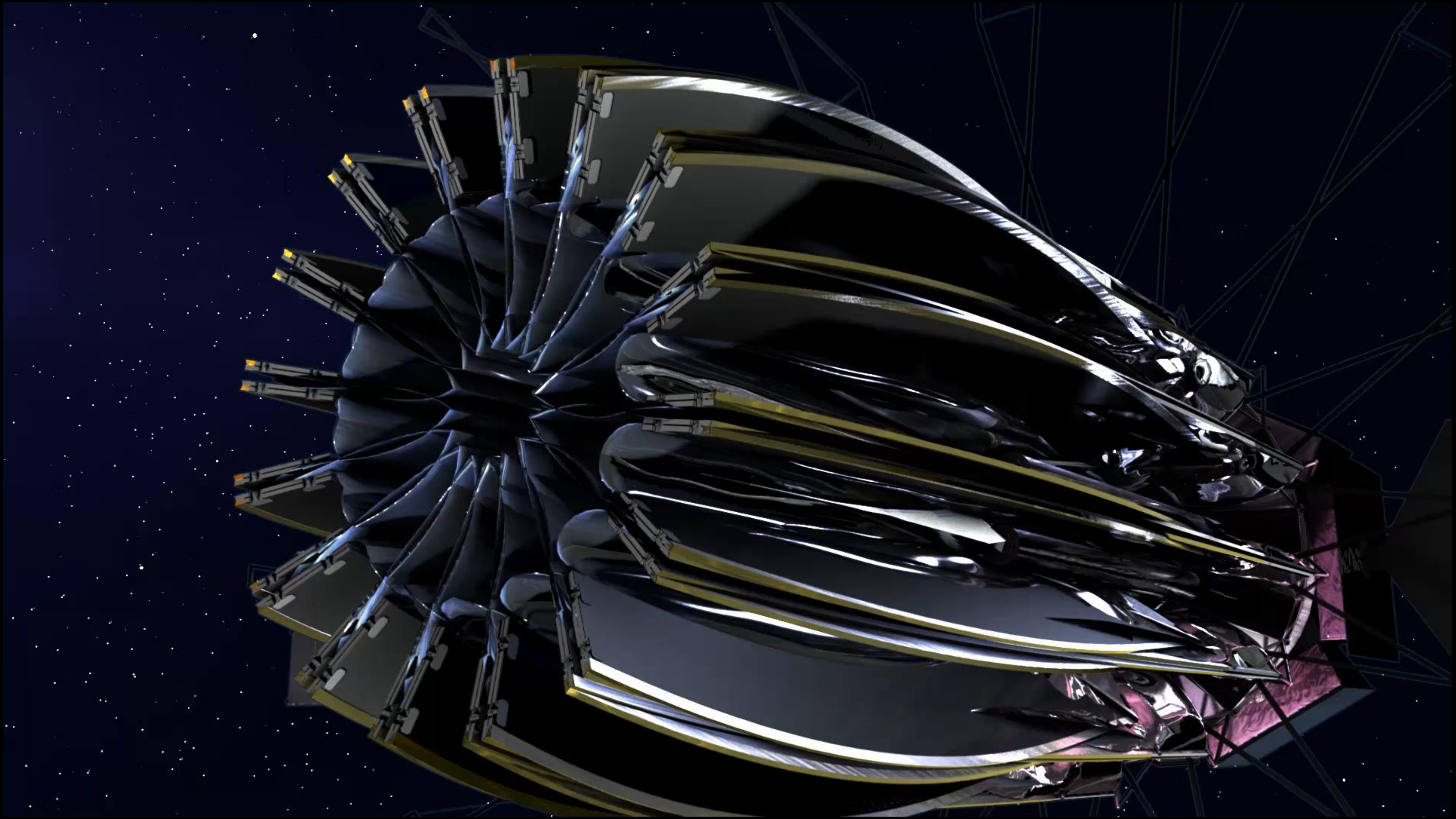
Furled and wrapped petal deployment concept (JPL)



Boom supported and folded petal deployment concept (Northrop Grumman)

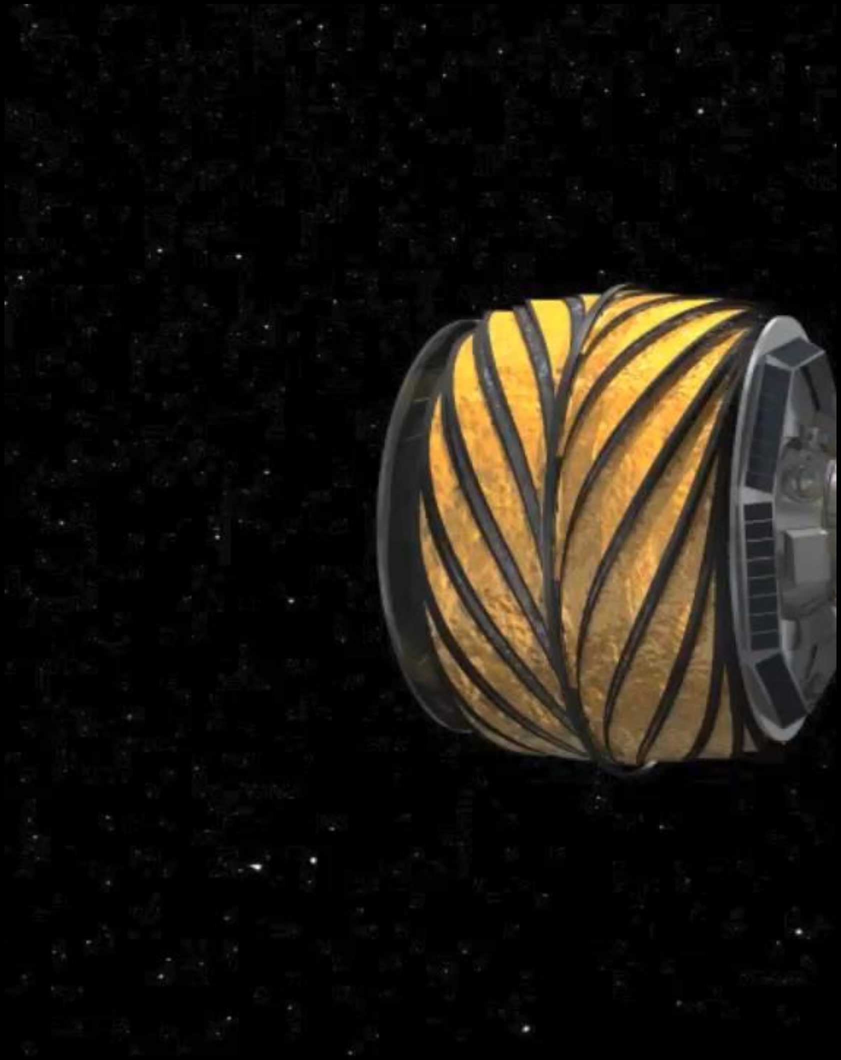
Folded Petal Deployment Architecture

Northrup Grumman Aerospace Systems



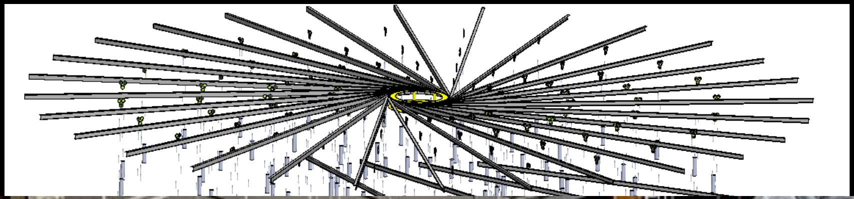
Wrapped Petal Unfurling

Jet Propulsion Laboratory

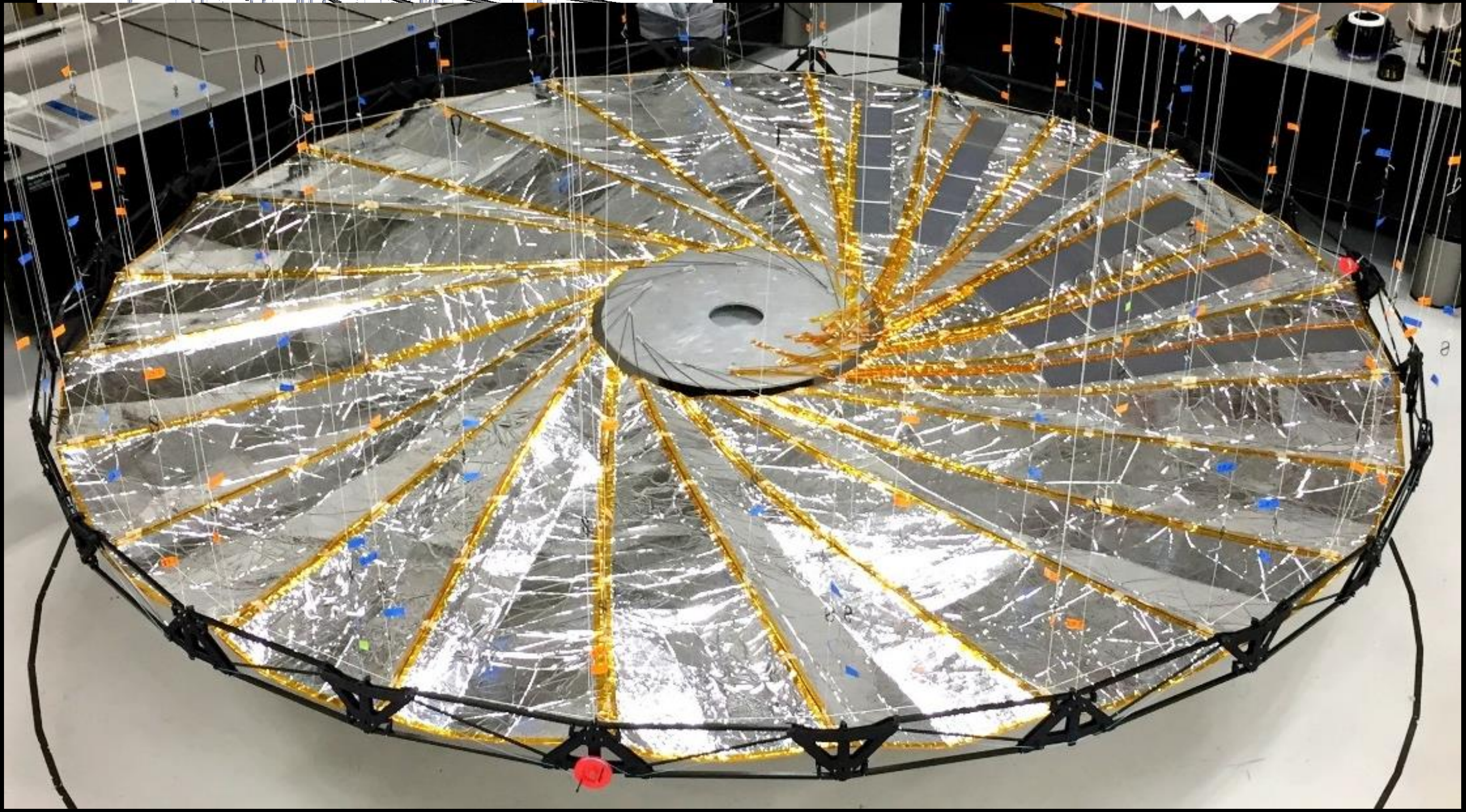


Optical Shield Testbed Gravity Offloading

SBIR Award: Roccor / Tendeg

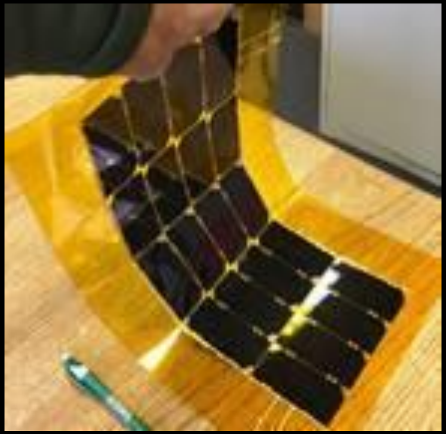


Roccor and Tendeg are made up of experts in composite materials, space mechanisms, and deployable structures

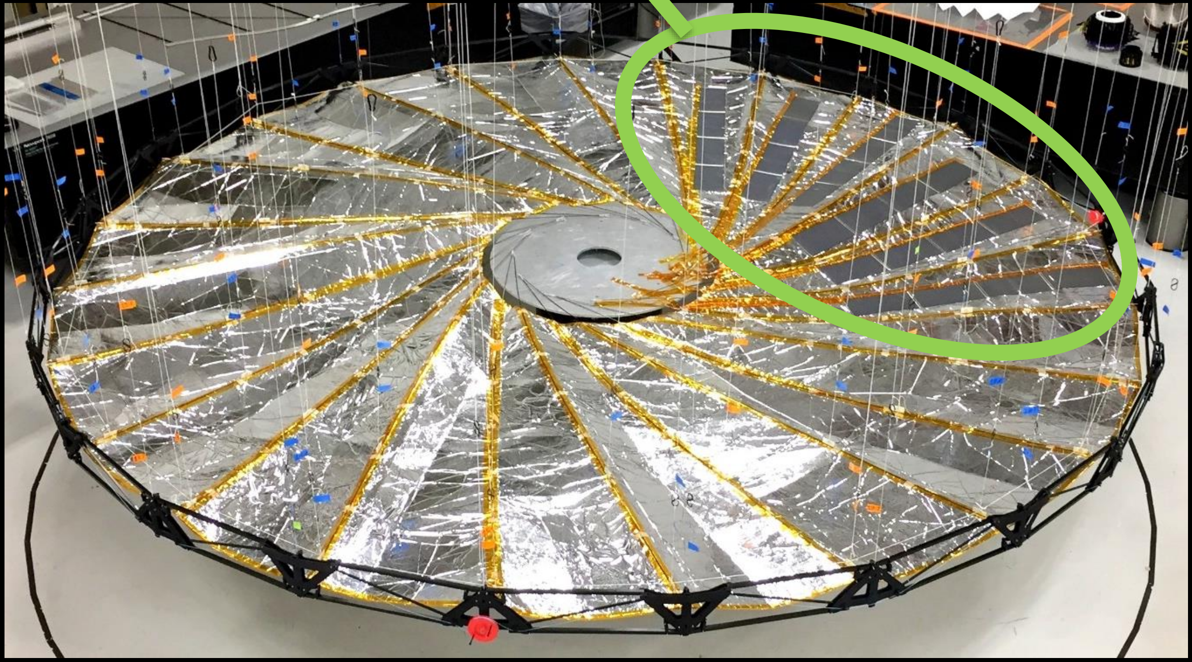


Optical Shield Solar Arrays

SBIR Award: Tendeg's Solar Array Integration

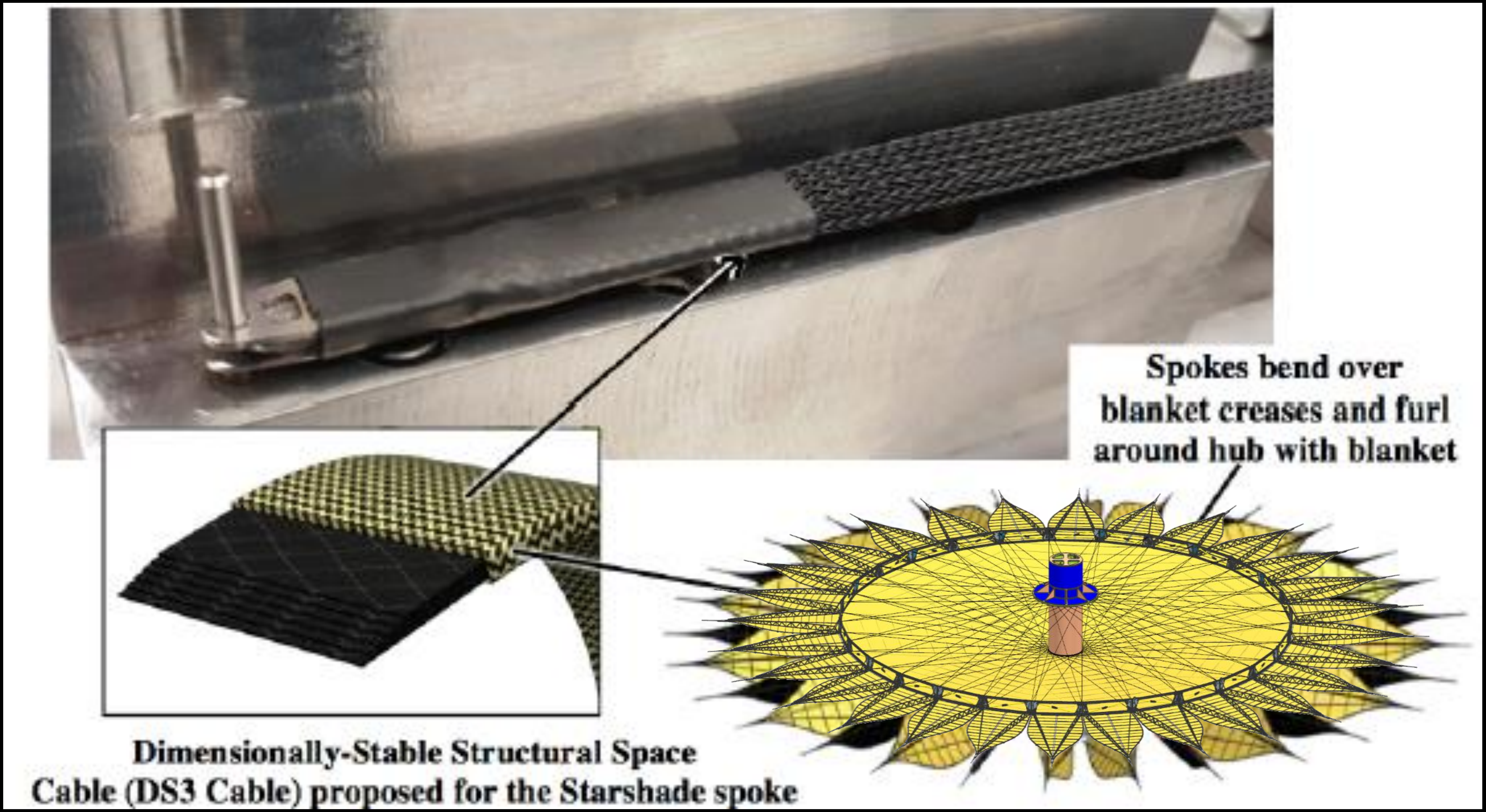


thin photovoltaic



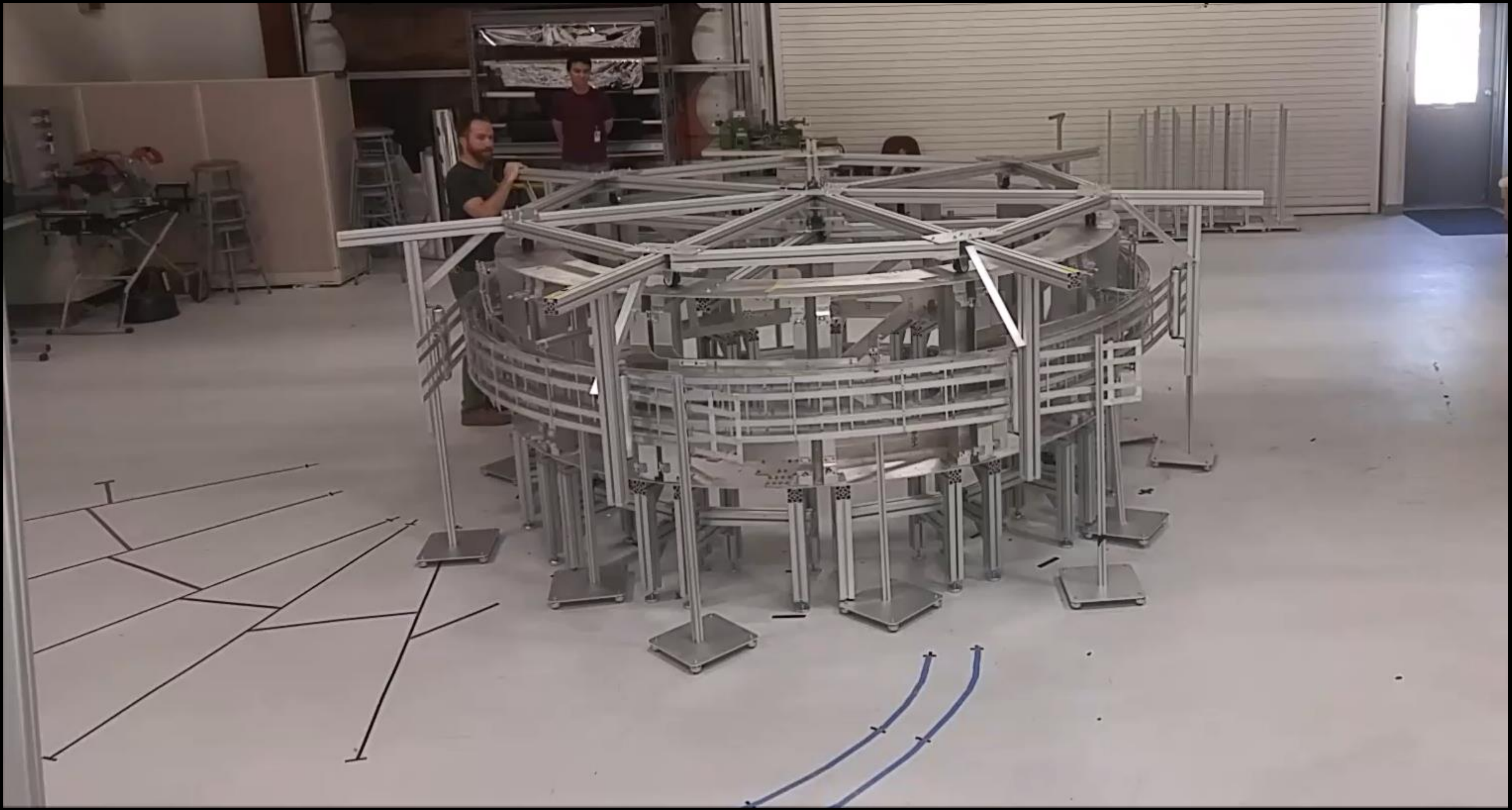
Inner Disk and Optical Shield Deployment

SBIR Award: Roccor's Dimensionally-Stable Structural Spoke



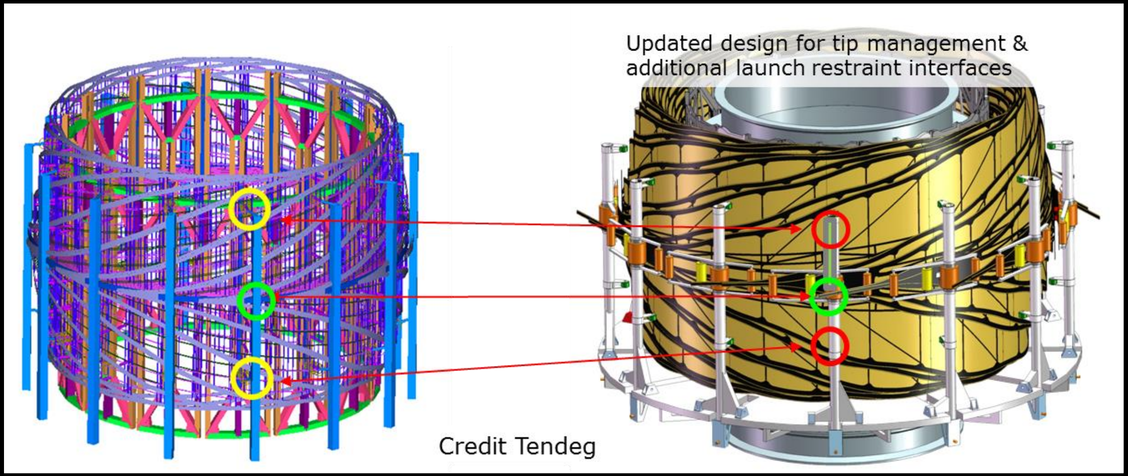
Petal Unfurler Testbed 1.0 Demo

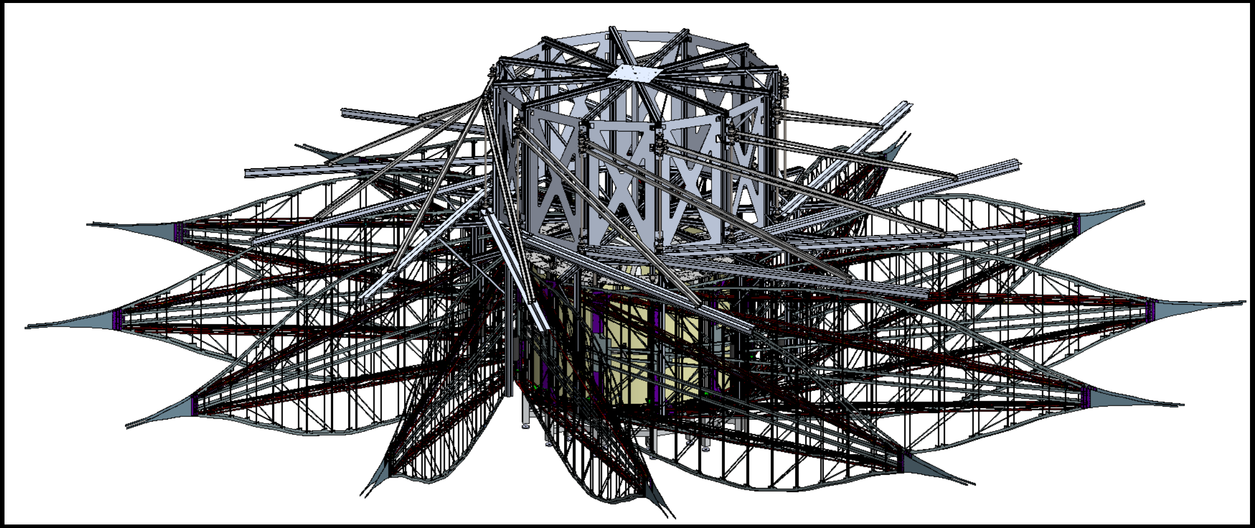
SBIR Award: Roccor and Tendeg



Petal Unfurler 2.0

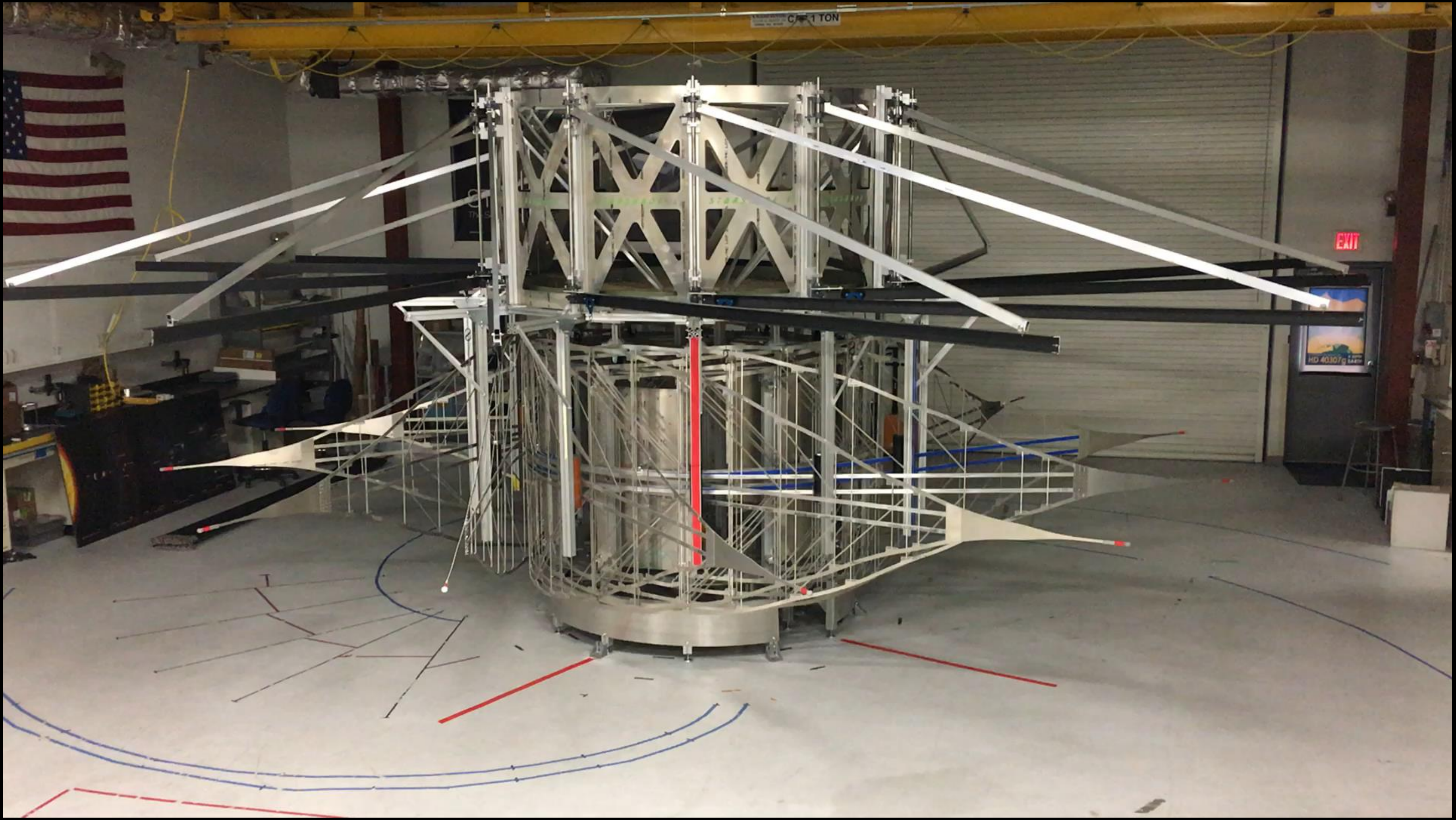
SBIR Award: Tendeg's Petal Launch Restraint and Unfurl System





Petal Unfurler Testbed 2.0 Gravity Offloading

SBIR Award: Roccor / Tendeg



Deployment Accuracy and Shape Stability

Petal Deployment Accuracy

Path to Close Gap:

- Complete Mechanical Deployment Architecture Trade Study by Q1 CY18
- Integrate an OS into the 10 m inner disk; deploy and demonstrate tolerances to show that the OS does not have a negative effect to meet petal position (using Roccor spokes)
- Optical shield material micrometeorite impact testing and model validation
- Deploy TRL 5 petal in unfurler testbed to demonstrate no contact (with simulation petals)
- Deploy at least ¼ of total TRL 5 petals at half/full scale

Optical Edge Development (Petals)

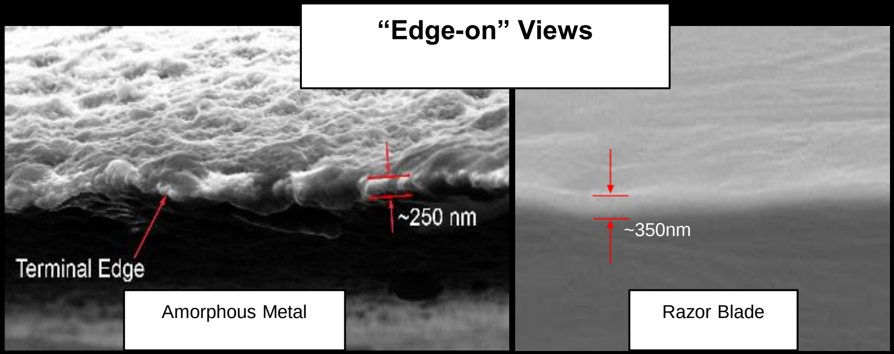
Scattered Sunlight Suppresion

Need:

- *Petal edges that reduce solar glint magnitude to levels below that of the apparent zodiacal dust*
    - ❖ *Edge radius (µm) * reflectivity (%) < 10 um%*
- *Petal edges that maintain precision in-plane profile for starlight suppression*

Current Capabilities:

- We know how to fabricate razor-sharp edges to minimize total area available for solar scatter/glint (photochemical etching)
- Amorphous metal is currently the primary material candidate
- We know how to achieve ultra-black surfaces that absorb sunlight incident to petal edges (low-reflectivity coatings)

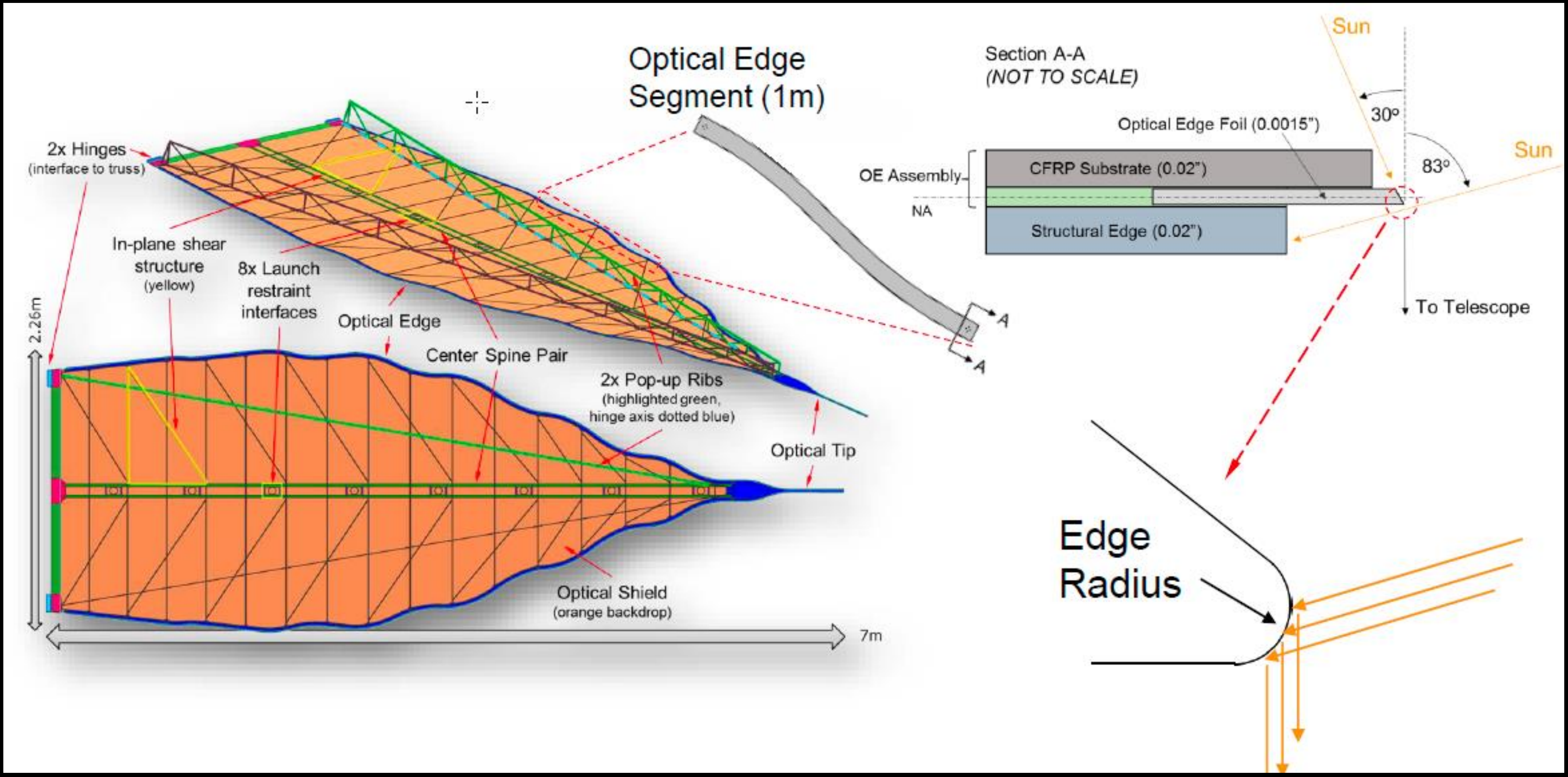


Comparable edge sharpness achieved between etched amorphous metal edges and Gem razor blades

Ultra-black surface coatings can potentially relax requirement on edge sharpness

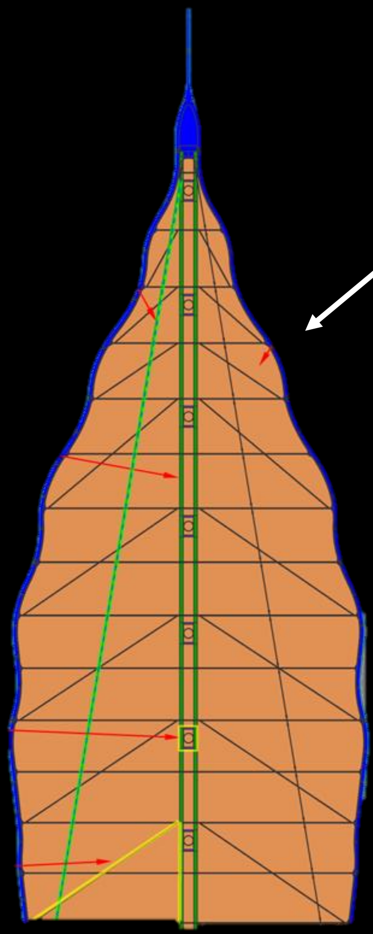
Petal Fabrication

SBIR Award: Tendeg's Petal Optical Edge Integration



Optical Edge Development

SBIR Award: Photonic Cleaning Technologies’ “Polymer Edge Coating-Based Contaminant Control”



To avoid solar glare and scatter interference petal optical edges must be razor-sharp <u>and</u> exceedingly clean

- *a few 100 µm dust particles on an edge scatters light comparable to the signal of an exoplanet.*

Photonic Cleaning Technologies proposes to develop a novel pourable, peelable, low adhesion, residueless polymer coating that will clean and protect the starshade’s amorphous metal edges from manufacture to launch.

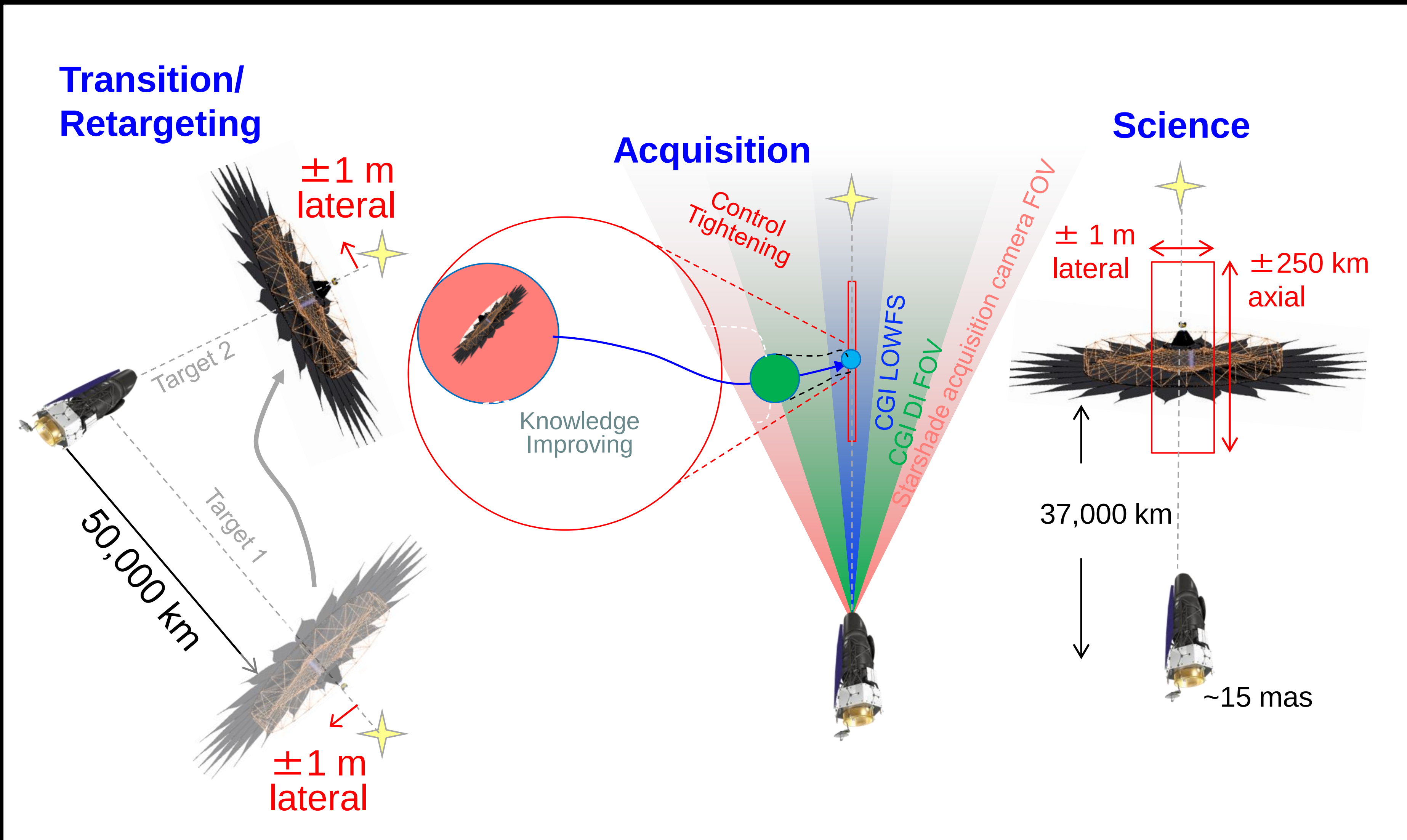
Optical Edge Development (Petals)

Starlight Suppression

Plan to Close Gap:

- Currently trading optical edge materials, manufacturing techniques, and coatings to compare solar scatter and diffraction results
- Plan to develop sub-scale proof of concept edge prototype that meets in plane profile and solar scatter performance by December 2017
- Integrate optical edge onto flight-like petal
  - Bonding material
  - Edge protection and handling
  - Edge-to-edge segment interface and joining
  - Fabricating larger segments, getting to flight size
  - Environmental test of flight-like segments, including mounting

Formation Flying
High Level Operations Concept



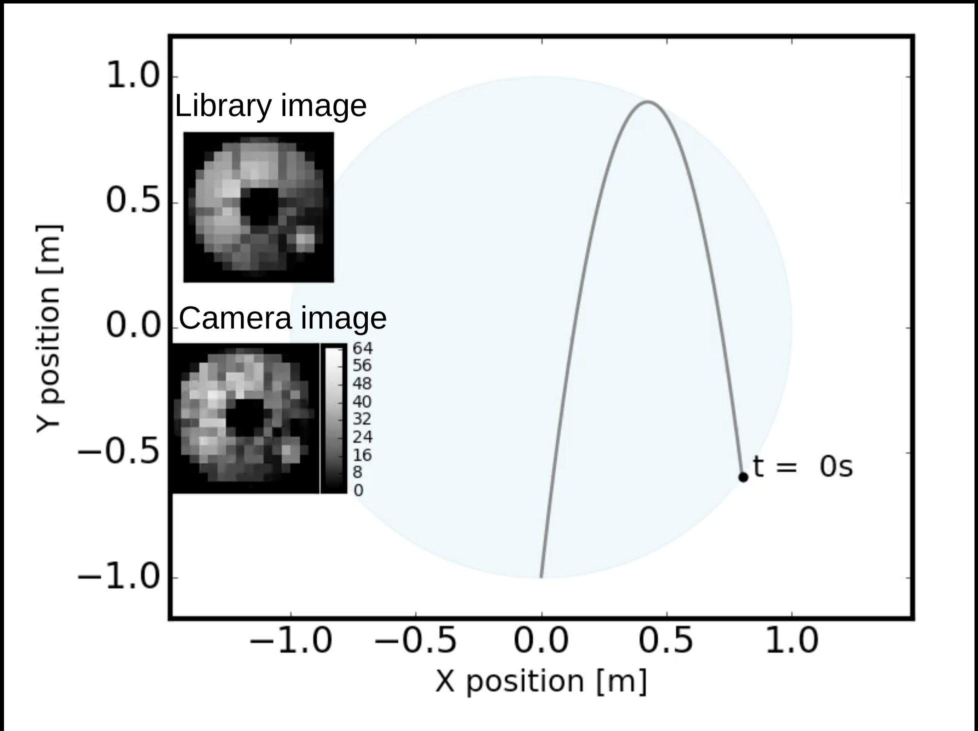
Formation Flying

Lateral Offset Sensing

Current Capabilities:

Pattern recognition approach developed while working WFIRST option

- Using pupil plane wavefront sensor and out-of-band stellar diffraction allows for accurate sensing at the ~cm level around all target stars
- Approach is being tested in the lab and the measurements compared with a model.



Guiding on an 8th magnitude, solar-type star. Trajectory fire occurs at 0s. Pupil plane camera exposure time is 1 second. Precision is 2 cm.

POC: Michael Bottom (JPL)

Formation Flying

Lateral Offset Sensing

Path to Close Gap

- Upgrade Formation Flying Testbed with lower diffraction optics
- Create library of simulated detector images of starshade’s laser beacon offset to the leaked starlight pattern.
- Computer match testbed image to a library of images to identify real off-set
- Develop control algorithm to work with testbed sensing data

Summary

- Starshade technology is progressing in all technology areas with the goal of an endorsement by the Decadal Survey and supporting a future WFIRST Rendezvous Mission
- Mechanical architecture trade study will establish a baseline design and permit final development and approval of a complete technology development plan to TRL 5 during the spring of 2018

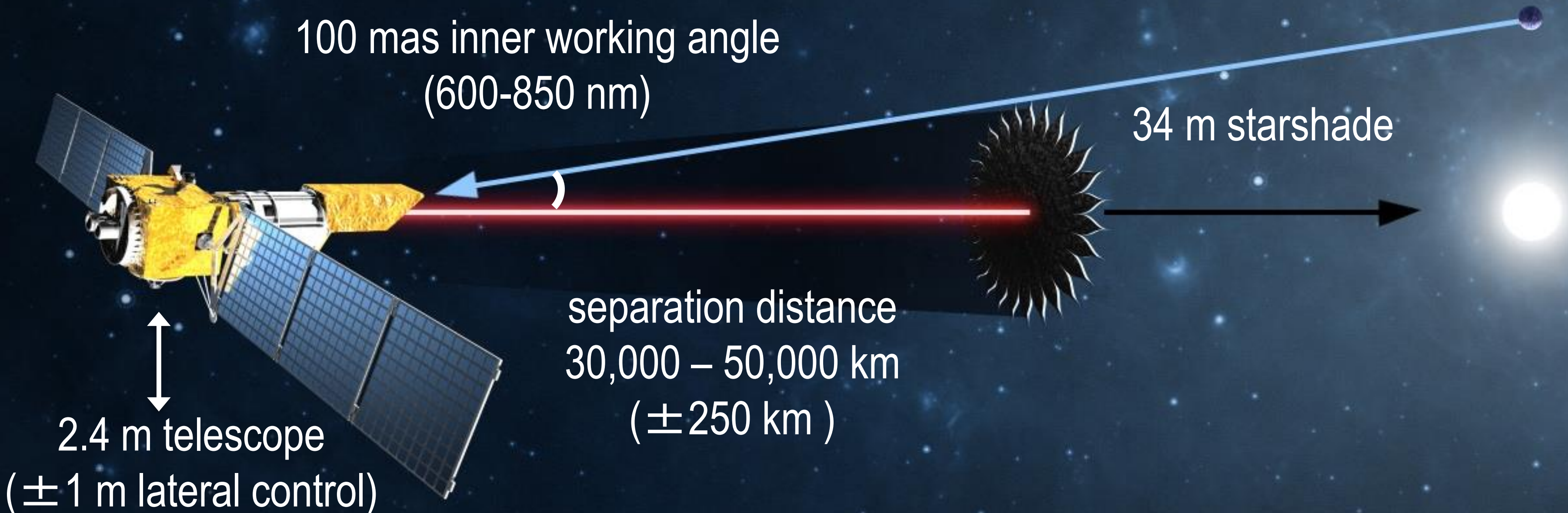
Jet Propulsion Laboratory
California Institute of Technology

This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

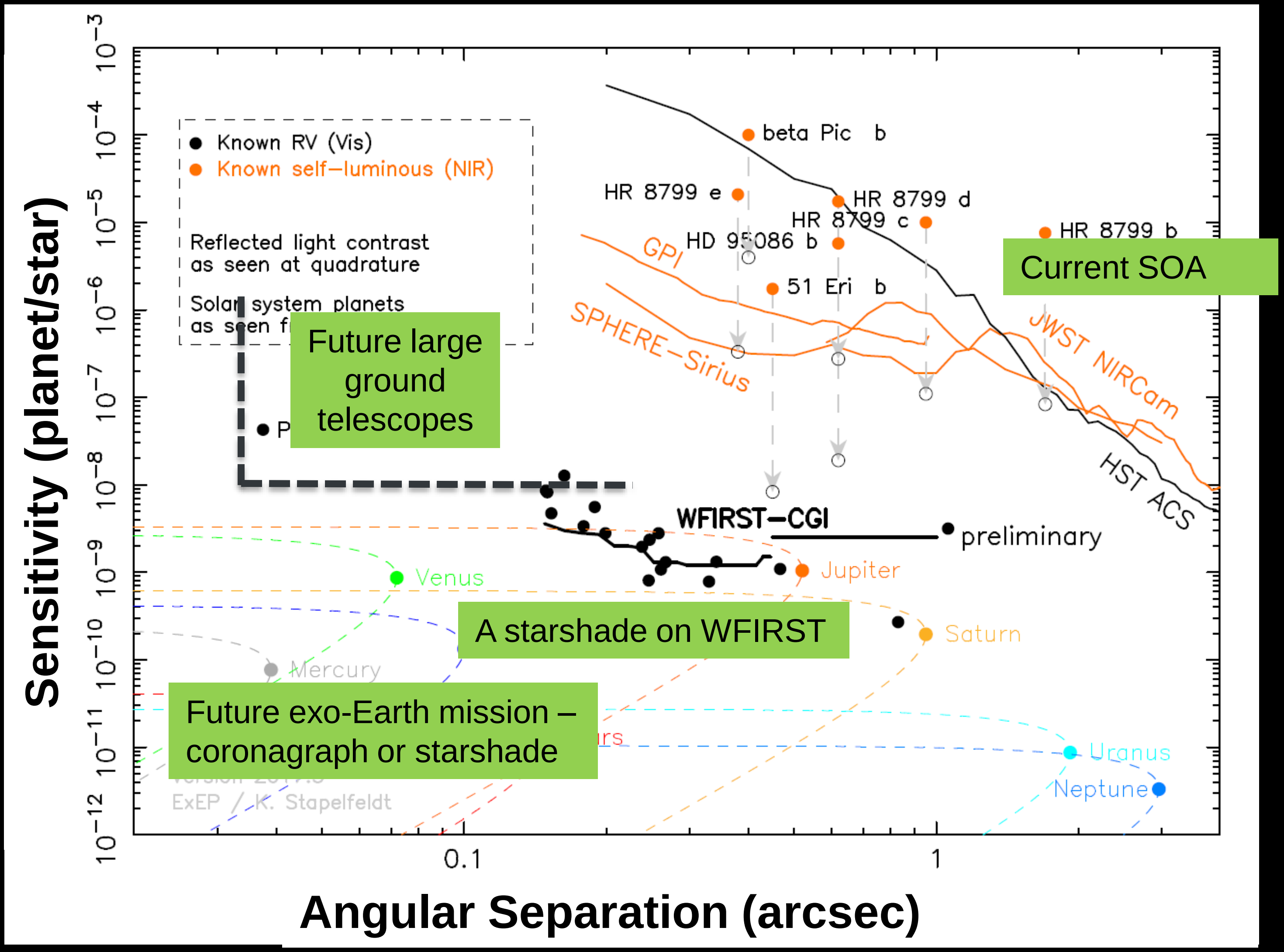
Additional Slides

Starshade

The hard stuff is done external to telescope



Starlight Suppression
State of Art vs Needs



Possible New Worlds Exoplanet Telescopes

Pending 2020 Decadal Survey

Example of Key TRL-5 Requirements

Quantified performance needs tied to error budgets, gap lists, Exo-S report

Technology Area	Key Performance Tolerances (3σ)	Proposed End-State Fidelity (TRL-5+)			Tested in Relevant Environment; Designed to Meet Life Rqmt	Performance Verification	Model Validation
		Fit	Form	Function			
Deployment Accuracy and Shape Stability	**Petal Shape and Stability**						
	In-plane envelope: ± 100 µm	High fidelity, full-scale	High-fidelity prototype	Required performance demonstrated	Deploy and thermal cycles	Measure shape after deployment and thermal cycles	CTE, CME, creep
					Temperature and humidity	Measure shape with optical shield at temp.	Shape vs. applied loads
					Stowed strain	Predict on-orbit petal shape with all errors	Shape vs. temperature
	Petal Deployment Accuracy						
	In-plane envelope: ± 1 mm	High fidelity, half-scale inner disk; scaling issues understood	High-fidelity prototype	Required performance demonstrated with critical interfaces	0-gravity and vacuum	Measure position after deployment cycles in air with negligible air drag and imperfect gravity comp.	CTE, CME, creep
					Temperature and humidity	Measure position with optical shield at temp.	Shape vs. applied loads
					Stowed strain	Analyze on-orbit petal shape with all errors	Shape vs. temperature
Formation Sensing and Control	**Bearing Angle Sensing and Control**						
	Sensing: ± 1 mas Control (modeling): ± 1 m	Medium fidelity, using small-scale starshade; scaling issues	Medium-fidelity prototype	Basic functionality demonstrated	Large separation distance	Measure angular offsets with brassboard guide camera (coronagraph instrument) that simulates PSFs and fluxes from beacon and star	PSFs bearing angle vs. signal
Contrast	**Scattered Sunlight**						
	Edge radius x reflectivity: ≤ 10 µm-%	High fidelity, full-scale petal with full-scale optical edges	High-fidelity prototype	Required performance demonstrated with critical interfaces	Same as for petal shape	Measure petal level scatter after environment tests at discrete angles	Scatter vs. sun angle Scatter vs. dust
					Sun angle	Measure coupon level scatter after environment tests at all sun angles	
					Dust in launch fairing	Analyze effect for on-orbit solar glint	
	Starlight Suppression						
	Test at a flight-like Fresnel: Contrast (test) < 10^{-9} (traceable to 10^{-10} system performance with validated model)	Medium fidelity, small-scale starshade; scaling issues understood	Medium-fidelity prototype	Basic functionality demonstrated	Space	Measure image plane contrast between 500-850 nm	Optical performance, sensitivity to perturbations

(to be concurred by a TAC at the end of Starshade Technology Formulation)

Inside the Starshade